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Research paper

Analysis of heterogeneous characteristics in a geothermal area with low permeability and high temperature

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ABSTRACT

An analytical methodology for reservoir characterization was applied in the central and southwestern zones of Los Humeros geothermal field (LHGF). This study involves analysis of temperature, pressure, enthalpy and permeability in wells and their distribution along the area. The wells located in the central western side of the geothermal field are productive, whereas those located at the central-eastern side are non-productive. Through temperature profiles, determined at steady state in the analyzed wells, it was observed that at bottom conditions (approximately 2300 m depth), temperatures vary between 280 and 360 °C. The temperatures are higher at the eastern side of central zone of LHGF. A review of transient pressure tests, laboratory measurements of core samples, and correlation of circulation losses during drilling suggest that permeability of the formation is low. The enthalpy behavior in productive wells shows a tendency of increase in the steam fraction. It was found that productivity behavior has inverse relation with permeability of rock formation. Further, it is observed that an imbalance exists between exploitation and recharge. It is concluded from the results that the wells located at central-eastern area have low permeability and high temperature, which indicates possibility of heat storage.

1. Introduction

The central zone of Los Humeros geothermal field (LHGF) shows contrasting results; the wells drilled at the west side are productive whereas those on the east side are unproductive. To evaluate this contrasting behavior a methodology was developed. Through this methodology it is possible to estimate the initial conditions of the reservoir, its reserves, useful life, and operation policies, among other aspects (Schatzinger and Jordan, 1999). In order to apply the optimal production techniques for improving productivity, the reservoir characterization models are used to simulate the behavior of the fluids under different sets of circumstances.

The LHGF is located inside the Plio-Quaternary volcanic caldera complex with less than 500 ka of age. This complex is located in the eastern part of the Mexican Volcanic Belt (Gutiérrez-Negrín and Izquierdo-Montalvo, 2010). The location of the field is at the border between Puebla and Veracruz states, approximately to 220 km of Mexico City, with latitude 19.68°N and longitude 97.45°W (Lorenzo-Pulido, 2008). The topographical level of the field varies between 2800 and 2900 masl and the average temperature at the surface (INEGI, 2013) is between −2 °C (in winter) and 15 °C (in spring). A location map of the LHGF within the Mexican Republic is shown in Fig. 1. Inside the main caldera three geological features are distinguished: the "Potreros" collapse, a semi-circular rim known as "Collapso Central" (CC) at the north of the field, and the "Xalapasco" crater at the south.

41 wells have been drilled since 1981, among which 18 of them are producers and 3 are injectors (Flores-Armenta et al., 2014). The wells drilled in the "CC" and in the "Xalapazco" areas are producers and because of this, new exploration drillings in the central part of the field were projected. Wells 23, 24, 25, 26 and 27 were drilled in the central area of the field. In these wells, average static temperature was determined close to 290 °C but at greater depths than those drilled at the "CC". High temperature and low permeability were determined in all these wells of the central eastern zone of the field (Torres, 1995). However, the wells in central-eastern area of

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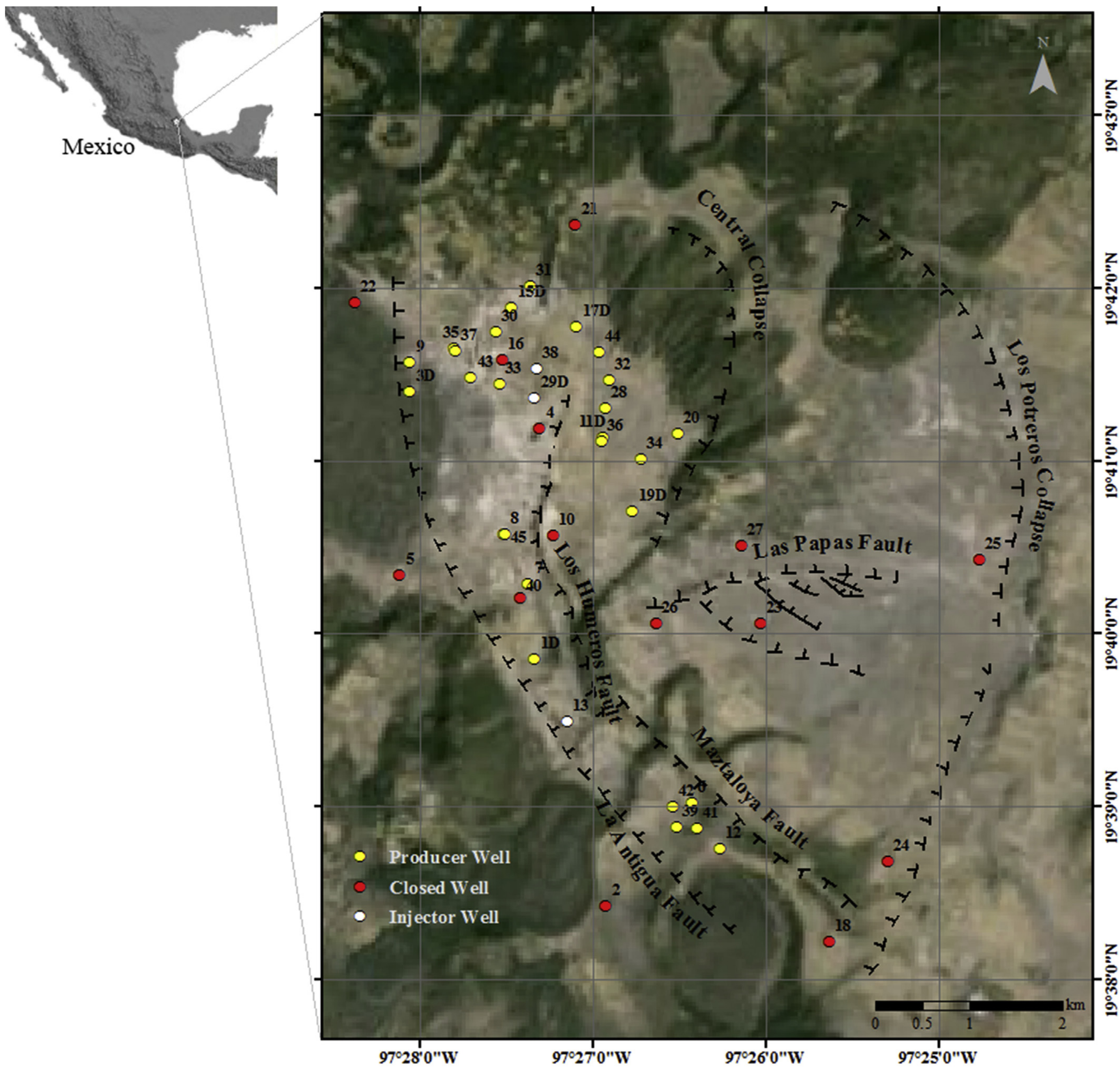

Figure 1. Location map of Los Humeros Mexico, geothermal field (LHGF) and existing wells; the producers with yellow mark, the closed (non-producers) with red mark, reinjection wells with green (the map was downloaded from Google earth and were included the wells and geological faults).

LHGF did not produce geothermal fluid, hence they were closed/abandoned. Due to low permeability conditions, and corrosion problems by acid condensed fluids, no more wells were drilled in this zone.

Permeability is a measure of the easy movement of fluid flow through rock. The permeability of rock results from pores, fractures, joints, faults, and other openings which allow fluids to move. High permeability implies that fluids can flow rapidly through the rock. Permeability and, by consequence the flow of fluids tend to decrease with depth because of the openings in the rocks are compressed from the weight of the overburden. According to Cedillo-Rodríguez (2000), the distribution of low permeability in rocks (granites and limestone) around Los Humeros caldera, combined with annular faults, isolates the geothermal reservoir from regional recharge. The recharge to the reservoir mostly occurs from rainfall transmitted through the fault system and fractures (Gutiérrez-Negrín et al., 2010a).

Based on updated data of the discharged fluids of the wells, reservoir fluids show enthalpy values greater than 2400 kJ/k, hence the field has been referred as a high enthalpy system (Arellano et al., 2003) and the values correspond to a thermodynamic steam dominated state (Tello, 2005). The exploitation from the wells of the field, except well 1, started with vapor dominated flow. As the operation time progressed, the steam fraction in the wells increased and gradually changed to dry steam. In this study, the mean values of main production characteristics of wells located in the central and southwestern zone of the field were considered. Significantly, this steam phenomenon in a geothermal reservoir can be accentuated by its overexploitation due to mass extraction without sufficient recharge water entrance (González-Partida et al., 2001; Tello, 2005; Martínez Reyes et al., 2010).

In this work, the available parameters (pressure and temperature logs, fluid circulation losses) obtained during drilling of wells (producers and closed) were analyzed. During drilling of wells, volumes of fluid circulating between its inlet and outlet are measured in order to maintain control on the formation pressure. Indirectly this measurement allows identifying qualitatively some permeable thicknesses along the well depth and supports election of appropriate interval to be tested with transient pressure tests. Results of transient pressure tests (porosity, permeability, skin factor, drainage radius, reservoir pressure) related to geological, geophysical and geochemical data give the technical support for taking decisions on the wells completion and their production interval.

The mass produced by wells is mainly high enthalpy steam and low volume of water; which is a mixture of low-salinity fluids of the sodium-chloride and bicarbonate-sulfated type with high content of boron, ammonia and oversaturated in silica and calcite (Barragán et al., 1991; López, 2006).

Fluids show evolution toward a fluid of one phase, decreasing the liquid fraction in the produced mixture. The changes in the composition of fluids (Arellano et al., 2015) suggest the existence of boiling conditions at depth. The observed tendency is related to a poor recharge of the reservoir.

The aim of this study is to apply a methodology for reservoir characterization in two neighboring zones (central and southwestern) of LHGF, in order to define the behavior of producer wells and the closed (non-producers).

2. Conceptual background of the area

The geothermal resource represents 2.94% to the total power generation in Mexico public services. Other generation sources are hydrocarbons (73%), hydro (14%), coal (7%), nuclear (3%) and wind (0.06%). According to Bertani (2012), Mexico is ranked in fourth place in installed geothermal capacity after U.S (3098 MW), Philippines (1904 MW) and Indonesia (1197 MW).

Zones of thermal springs are concentrated mainly along the Mexican volcanic belt although are distributed throughout the country. Most fluids are derived from surface waters that have percolated along permeable pathways such as faults (Lenhardt and Gotz, 2015). The hydraulic connectivity and hydrothermal fluid circulation occur through faults and fractures in volcanic systems, allowing deep hot fluids to ascend.

The net geothermal electric capacity in Mexico is 958 MW; installed into four geothermal fields: Cerro Prieto (720 MW), Los Azufres, Mich. (188 MW), Los Humeros Pue., (40 MW) and Las Tres Vírgenes BCS (10 MW). 37 power plants of several types (condensing, back pressure and binary cycle) between 1.5 and 110 MW operate in these fields, fed by 229 geothermal wells whose brine is injected in 29 wells. The production wells have depths between 600 and 4400 m and global water-steam ratio (WSR) is about 1.2 (Flores-Armenta and Gutiérrez-Negrín, 2012).

These wells are distributed as follows: Cerro Prieto (160 productions and 18 injections), Los Azufres (37 productions and 6 injections), Los Humeros (18 productions and 3 injections), and Las Tres Vírgenes (3 productions and 2 injections) (Gutiérrez-Negrín, 2012).

The LHGF is one of the four geothermal fields currently operating in Mexico, and is ranked third in geothermal energy production for electricity generation. The fluids produced by the wells of this field are the two phase mixture of low salinity (Bernard-Romero and Taran, 2010; Gutiérrez-Negrín et al., 2010b). The mean depth of producer wells is about 2300 m (500 masl). To date the field has an installed capacity of 40 MW with eight back-pressure units of 5 MW each. An average of 18 production wells that produce around 500 tons of steam per hour fed the power plants (Flores-Armenta et al., 2014).

The Los Humeros caldera lies near the intersection of two major volcanic provinces, the northeastern part of the calc-alkaline Trans-Mexican Volcanic Belt and the southern end of the alkaline volcanic series of the eastern Cordillera. It is associated with the subduction of the Cocos Plate along the middle American trench (Verma, 1983).

The geology of the area has been studied by Yañez and García (1982), Ferriz and Mahood (1984), Campos-Enríquez and Garduño-Monroy (1987), Cedillo-Rodríguez (1997), among others. The local basement of the LHGF is formed by a Paleozoic metamorphic complex, a Mesozoic folded sedimentary sequence formed by chlorite-muscovite shales and lower Tertiary syenitic and granodiorite intrusions and Pliocene andesites. The latter were emplaced through faults in the boundary of the field. The LHGF has a complex geologic structure with a fluid flow controlled by fracturing. The hydrologic model and its subsurface geology have been described by several authors (Viggiano and Robles, 1988; Cedillo-Rodríguez, 1997; Gutiérrez-Negrín et al., 2010a). Four basic units with variable thickness and different lithologies have been identified (Viggiano and Robles, 1988; Cedillo-Rodríguez, 1999). Each unit includes layers of basalts, dacites, tuffs and rhyolites. However, not all of them are observed in every well. These lithological units are shown in Table 1. The reservoir base is mainly composed by limestones and subordinates shales and flint lenses, which were folded.

The Unit 1 is related to subsuperficial deposits, the Unit 2 is the seal cap, the Unit 3 is the reservoir and the Unit 4 is the reservoir base.

The Los Humeros caldera has dimensions of 21 by 15 km but younger volcanic rocks obscure its margins, except in the northeast quadrant where there is a topographic rim over which later andesites flowed. The oldest rocks of the caldera are porphyritic andesites and ferrobasalts of the "Teziutlán" formation with ages

Table 1
Main lithological units and characteristics of the subsurface found in LHGF (from Viggiano and Robles, 1988; Cedillo-Rodríguez, 1999; Gutiérrez-Negrín et al., 2010a).

Unit	Description	Age	Thickness (m)	Characteristics
1	Post-caldera volcanism: andesites, basalts, rhyolites, dacites, tuffs, ashes, pumicies	Quaternary (<100 Kyr)	Minimum: 90 Maximum: 1010	Shallow hot and cold aquifers, medium to high permeability
2	Caldera volcanism: ignimbrites Xaltipan and Zaragoza, with andesites, pumicies, rhyolites, tuffs	Quaternary (510–100 Kyr)	Minimum: 185 Maximum: 880	Aquitard acting as a seal-cap, low permeability
3	Pre-caldera volcanism: hornblende andesites and augite andesites (Teziutlán) with tuffs, basalts, dacites, rhyolites	Tertiary (Miocene–Pliocene) (10–1.9 Ma)	Minimum: 90 Maximum: 2600	Geothermal reservoir, medium to low permeability
4	Basement: limestones and subordinated shales (Pimienta and Tamaulipas superior formations), marble, skarn, hornfels, granitic rocks and minor diabasic and andesites dikes	Mesozoic–Tertiary (Jurassic–Oligocene) (140–31 Ma)	Minimum: 13 Maximum: Unknown	Low permeability, high temperature

Table 2
Properties of rock formation, determined from measurements laboratory applied to core samples carried out by Contreras et al. (1990).

Well	Depth (m)	Elevation (masl)	ϕ	ρ (bar/m^3)	K (mD)	K (m^2)	k_T (W m^{-1} °C^{-1})	C_p (J kg^{-1} °C^{-1})
2	616–619	2292–2289	19.7	2160	0.019	1.875E-14	1.54	1047
4	907–910	1916–1913	19.4	2240	0.086	8.488E-14	1.96	1047
10	1469–1473	1376–1372	6.1	2620	0.026	2.566E-14	1.61	1089
	1825–1830	1020–1015	6.5	2650	0.008	7.895E-15	2.29	963
15	1410–1412	1391–1389	5.2	2520	0.001	9.869E-16		
17	2227–2230	579–576	20.5	2600			2.74	1214
18	1750–1753	1258–1255	14.7	2340	0.005	4.935E-15	2.42	921.1
19	1769–1771	1045–1043	11.5	2460	0.147	1.451E-13	1.91	1172
20	1403–1406	1430–1427	15.8	2270	0.059	5.823E-14	2.19	1047
22	663–666	2107–2104	18.1	2250	0.096	9.474E-14	1.96	1089
	1110–1113	1660–1657	9.1	2460	0.001	9.869E-16		
23	1924–1927	948–945	13.9	2370	1.252	1.236E-12	1.82	1089
24	2297–2300	652–649	11.6	2370	0.07	6.908E-14	2.14	1130
	2844–2847	105–102	12.7	2450	3.829	3.779E-12	1.62	1047
25	1710–1713	1102–1099	4.1	2760	0.001	9.869E-16		
26	1810–1813	1066–1063	4.5	2670	1.873	1.849E-12	1.95	1005
27	1500–1503	1370–1367	10.1	2400	0.145	1.431E-13	1.89	1130
29	1200–1203	1617–1614	18.4	2250	0.334	3.296E-13	1.86	1047

Table 3
Experimental data of the Klinkenberg permeability of a silicified rock (Well 26) and a low hydrothermal altered rock (Wells 27 and 28), carried out by Izquierdo et al. (2011).

Well	Klinkenberg permeability		Tension strength
	(mD)	(m^2)	(MPa)
26	2.18	2.1515E-12	2.21
27	0.096	9.4744E-14	4.89
28	0.073	7.2045E-14	4.53

>1.6 Ma, and a volume of 60 km^3. At 0.46 Ma before the present the major collapse of the main caldera was initiated by the eruption of the mostly non-welded “Xáltipan” ignimbrite, with an estimated volume of 115 km^3, and estimated maximum thickness at outcrop of >150 m.

This ignimbrite is 250 m thick in Well 2 (at south of the field). Its pumice is an aphyric high-silica rhyolite that is overlain by air-fall lapilli tuffs ranging from rhyodacite to andesite. The amount of collapse estimated by determining the offset of the lower contact of the ignimbrite is approximately 450 m. The next pyroclastic eruption was the “Faby” tuff with a volume of approximately 10 km^3 and age 0.2 to 0.3 Ma, which covered the “Xáltipan” ignimbrite discordantly, with an aggregate thickness of 16 m. This was followed by a quiescent period when gullying and lake deposits formed.

The next pyroclastic eruption was the “Zaragoza” tuff with an approximate volume of 12 km^3, consisting of non-welded ignimbrite with lithic-rich airfall tuff above. This was associated with the collapse of the 10 km diameter of “Los Potreros” sub-caldera in the southern part of the main “Los Humeros” caldera. This “Zaragoza” tuff with an age approximately 0.1 Ma, consisting of rhyodacite tuff, contains pumice lapilli with phenocrysts of pyroxenes, plagioclase, and Fe-Ti oxides. Based on an apparent displacement of 375 m of the base of the “Xáltipan” tuff between Well 2 outside the collapse and Wells 3 and 4 within it, the estimated volume of the magma extruded during this collapse was 17 km^3. There was then a change to more mafic magmas (Ferriz and Mahood, 1987).

The next big eruptions were andesites (volumes 6 km^3, with an age of 0.04–0.02 Ma), and rhyodacites (10 km^3, with an age of 0.03–0.02 Ma). The most recent eruptions were olivine basalts with a volume of 0.25 km^3 with an age of <0.02 Ma (Ferriz and Mahood, 1984).

The location of this zone coincides with the upflow zone of the geothermal system and probably with the magmatic chamber at depth (Bundschuh and Zilberbrand, 2011). Norini et al. (2014) related that main ring faults of the calderas are buried and sealed with widespread post-caldera volcanic products and for this reason probably do not have enough secondary permeability. Faults can represent connections to deep with hot rock formations and allow deep groundwater migrate to shallower depths.

Geothermal fluids at Los Humeros are contained in Tertiary andesites, covered by a series of Quaternary ignimbrites with low permeability considered as the cap rock of the geothermal reservoir. Andesites are altered by hydrothermal minerals such as calcite, quartz, chlorite, epidote, low amounts of leucoxene, hematite and pyrite. Other alteration minerals reported include smectites, kaolinite, illite and small amounts of zeolites, anhydrite, amphiboles, garnet, diopside and wollastonite (Viggiano and Robles, 1988; Quijano-León and Gutiérrez-Negrín, 2003).

3. Results

The productivity in the central zone of the LHGF is contrasting. The producer wells involved in this study (1, 6, 7, 12 and 39) are located at the western north and south side of central zone of the field. The closed Wells (23, 26 and 27) (non-producers) are grouped at the eastern side of central zone of LHGF. By using pressures, temperatures and circulation losses, measured in both types of wells (producers and closed) graphs of their profiles were constructed. Production parameters such as flow rate, steam fraction, enthalpy and pressure (these last two at bottom conditions) were used to feed the flow simulation program (Gunn and Freeston, 1991). It can be seen from Fig. 1 that the closed wells analyzed are close to “Las papas”, “Las víboras” and “Los Humeros” faults.

3.1. Behavior features of the field

Pressure and temperature at initial reservoir conditions can be used as a reference level for comparing its evolution along different stages of its operative life. Besides the low permeability of the rocks, the field is characterized by average steam fractions of 0.85 in the produced fluid from wells.

In this study, the fluid circulation losses during drilling are used only as a qualitative reference of the well permeability. From the measurements, it is observed that at shallow depths circulation losses are up to 50 m^3/h, and has no correlation with the geothermal reservoir. The circulation losses can be an indicative of permeability formation during drilling and is useful for suggesting the drilling stops and carry out thermodynamic measurements and transient pressure tests. Sometimes it would be necessary to continue drilling due to thermodynamic conditions or permeability determined from transient pressure test is not enough to support geothermal production conditions. Detection of circulation losses before the scheduled depth of the well, allows exploring new intervals or confirm predictions of geological and geophysical surveys. The determined mean values of capacity index (kh) from transient pressure tests carried out at the completion stage of the wells vary in the rank from 0.15 to 0.52 (E^{-12}) m^3, with skin factor (s) between 2 to 4 (Torres, 1995; Lorenzo-Pulido, 2008). From transient pressure test carried out after thermal stimulation in some of the wells of LHGF, capacity indices (kh) determined vary between 1.2 to 3.1 (E^{-12}) m^3 (Sánchez-Luviano et al., 2015). Permeability measurements carried out in different fragments of core samples of some wells from the field (Contreras et al., 1990) are shown in Table 2. Besides permeability (K); porosity (ϕ), rock density (ρ), thermal conductivity (k) and specific heat (C_p) were also determined in the core samples. The rock density is inverse function of permeability and, direct function of thermal conductivity (k) and specific heat (C_p).

From Table 2, the average absolute permeability (Bundschuh and Suarez-Arriaga, 2010) separately is: for matrix (0.071 mD) and for fractures (2.318 mD). Experimental data of a silicified rock (Well 26 at 2000 m deep) and a low hydrothermal altered rock (Wells 27 and 28) carried out by Izquierdo et al. (2011) are shown in Table 3. Permeability data are higher for the silicified rock compared to hydrothermally altered andesites. Tension strength (Brazilian test) of the silicified rock is almost half of the altered rocks. As the rock is more altered, the properties of the rock are different from those of the less altered. Deep rocks show microfractures sealed by quartz or by hematite; fractures are observed in cores from the upper andesite. Data of Klinkenberg permeability are different in both andesites. Authors suggest that the contact with an acid fluid bleached, leached and silicified the rock, leaving the porous mass of rock (Izquierdo et al., 2009).

In the producer wells, it has been observed that influence parameters are high temperature, small production thicknesses and low permeability of the rock. From production measurements, calculated enthalpies are greater than 2400 kJ/kg in producer wells of the west and southwestern of central zone of the field with WSR less than 0.5. Wells 1/1D are liquid dominant and their enthalpy varies between 1100 and 1300 kJ/kg (Arellano et al., 2003). Cumulative productions of steam, liquid and enthalpy behavior of wells operating in LHGF for a period of 25 years are shown in Fig. 2.

Enthalpy was calculated by using flow simulator (Gunn and Freeston, 1991) which uses the mass flow rates of steam (W_s) and liquid (W_w) and the known enthalpies of steam (H_s) and liquid (H_w) derived from steam tables at the corresponding pressure, the total enthalpy of the mixture (H_T) can be calculated by a heat and mass balance equation:

$$H_T = \frac{W_s H_s + W_w H_w}{W_w + W_s} \quad (1)$$

In the plot of Fig. 2, the enthalpy values of the first two years belong only to Well 1, because at that time there were no more wells under production. After ten years of operation, the Well 1 declined its production quickly and was replaced by a deviated well in the same hole, called as Well 1D. Fig. 2 shows appreciable difference the rate of produced steam and produced liquid, along operative life of the field. Measurements carried out in these wells during production stage in conjunction with flow simulators allowed to determine the bottom hole conditions. The plot of enthalpy-pressure shown in Fig. 3, represents the thermodynamic saturation state of the fluid produced by Wells 1/1D. Fig. 4 shows a similar diagram (pressure-enthalpy) using production data of the Well 7. In both figures it can be seen the difference in saturation state of produced fluid by each well.

Thermodynamically, the ratio between steam mass (m_s) and total mass (m_t) is defined as the mixture quality (X) [i.e. (m_s/m_t), where, $m_t = m_s + m_f$, with m_f as liquid mass]. From the graph of Fig. 3, it is possible to identify that the quality of the produced fluid

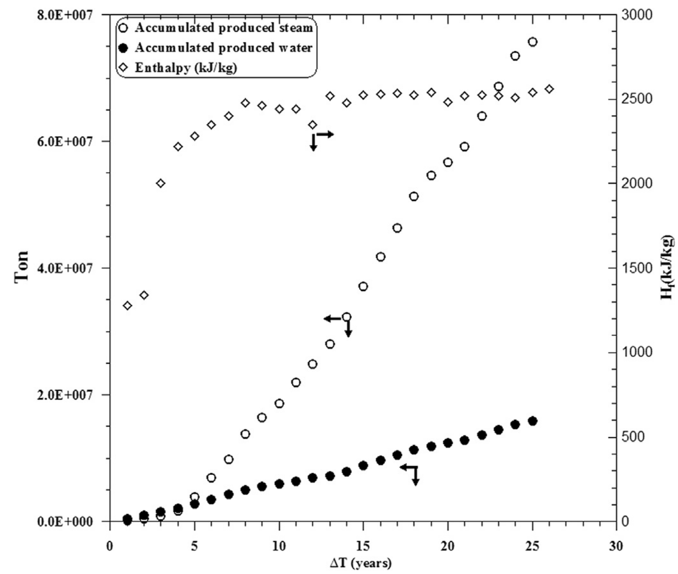

Figure 2. Graph showing the behavior of enthalpy, and cumulative flows of produced steam and liquid during operative life of LHGF wells.

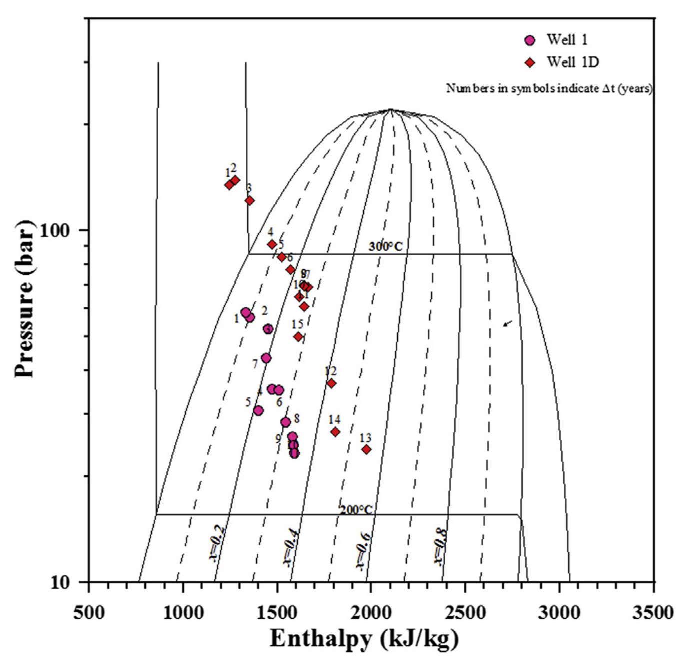

Figure 3. Graph showing enthalpy pressure of Wells 1/1D; it can be seen that the average steam fraction of these wells is in the order of 0.4.

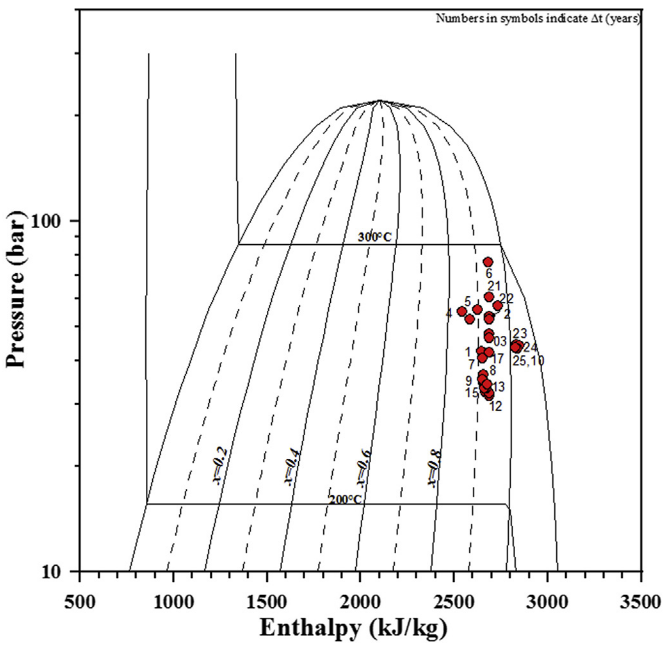

Figure 4. Thermodynamic behavior of Well 7 along its operative life; it can be seen that the average steam fraction of the well is 0.95.

in both wells varies along production time. While Well 1 shows a variation in quality of the fluid between 0.1 to 0.35, the quality in Well 1D varies from liquid phase to a value approximately 0.4.

The mass flow quality value of the Wells 1/1D, differs substantially. The quality of the produced fluid in the majority of the wells is greater than 0.7 whereas that of the Well 1/1D is 0.4. An example of this is the Well 7, shown in Fig. 4, whose average quality is 0.95. For most of the wells of the field, the observed trend is toward high steam fraction. As can be seen in Fig. 1, Wells 1/1D and 7 are neighbors; however from thermodynamic point of view, their productions are different.

Wells 1/1D (producers) are located at the western side of the central zone of LHGF while Wells 23, 25, 26 and 27 (those closed), are located at eastern side of this same central zone.

For closed wells, data corresponding to their drilling and completion stages were collected. Circulation losses (50 m^3/h), during drilling were recorded at shallow depths only and in small thicknesses where the ignimbrite was present. At depths high temperatures were logged, but the formation was neither permeable nor producing.

3.2. *Analysis of wells located in central area of Los Humeros geothermal field*

The locations of studied wells in central zone of the LHGF are shown in Fig. 5. A clear grouping of producer and the closed wells (non-producers) can be observed. Temperatures in producer wells are found to be higher than 300 °C at depths greater than 2000 m. Hence, except Wells 1/1D, all the wells in the field were drilled to a depth greater than 2000 m.

From the measurements carried out during drilling in the closed wells (non-producers) (23, 25, 26 and 27), small fluid circulation losses (between 6 and 20 m^3/h) were found. Temperatures at pseudo steady-state were obtained using measurements at the longer periods. Correlations of temperature profiles at pseudo steady state, and fluid circulation losses of Wells 23, 25 and 26 are shown in Figs. 6–8. The measured temperatures in these wells are in the order of 290 °C, but only at depths greater than 2500 m depth (300 masl). Furthermore, the profiles of calculated heating indices are also shown in Figs. 6–8. Heating index (HI) represents the velocity of rock heating after that disturbance caused by drilling fluid ceased. It is determined using two temperature measurements at

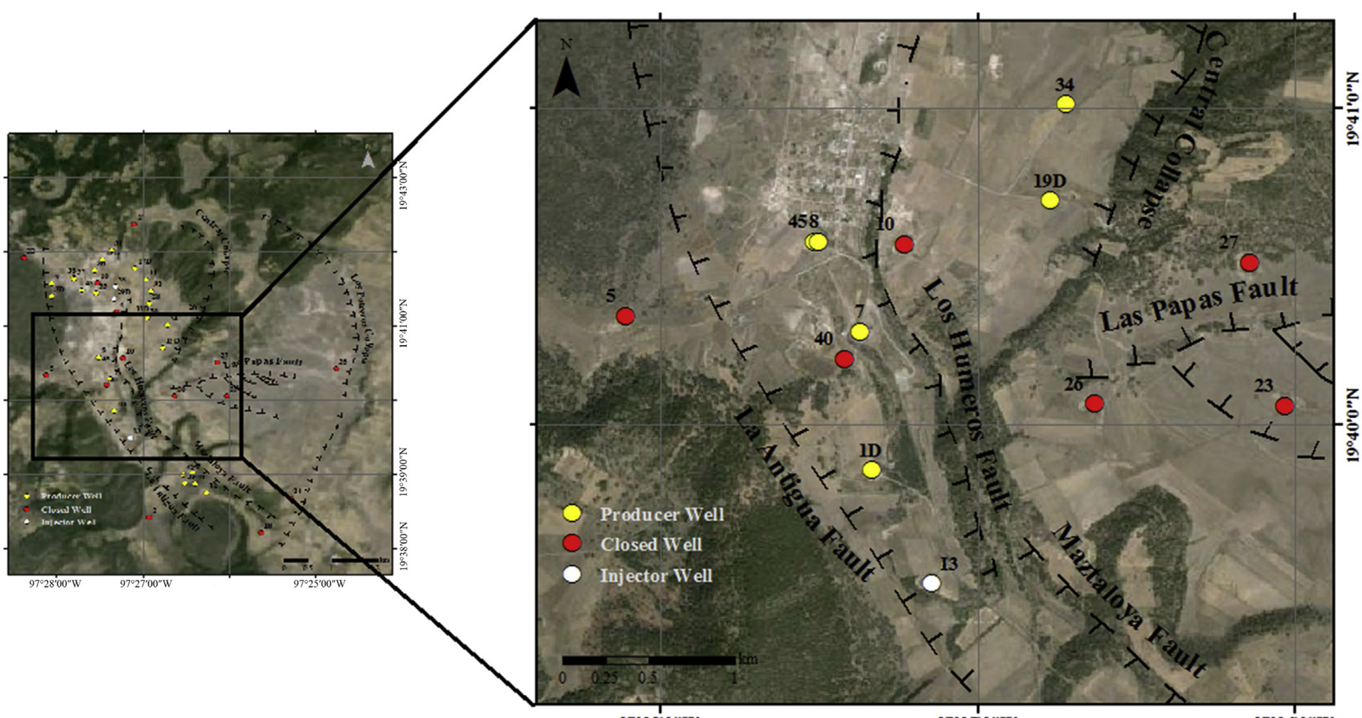

Figure 5. Location map of wells located at central zone of LHGF. It can be seen the closeness between producer wells and those closed.

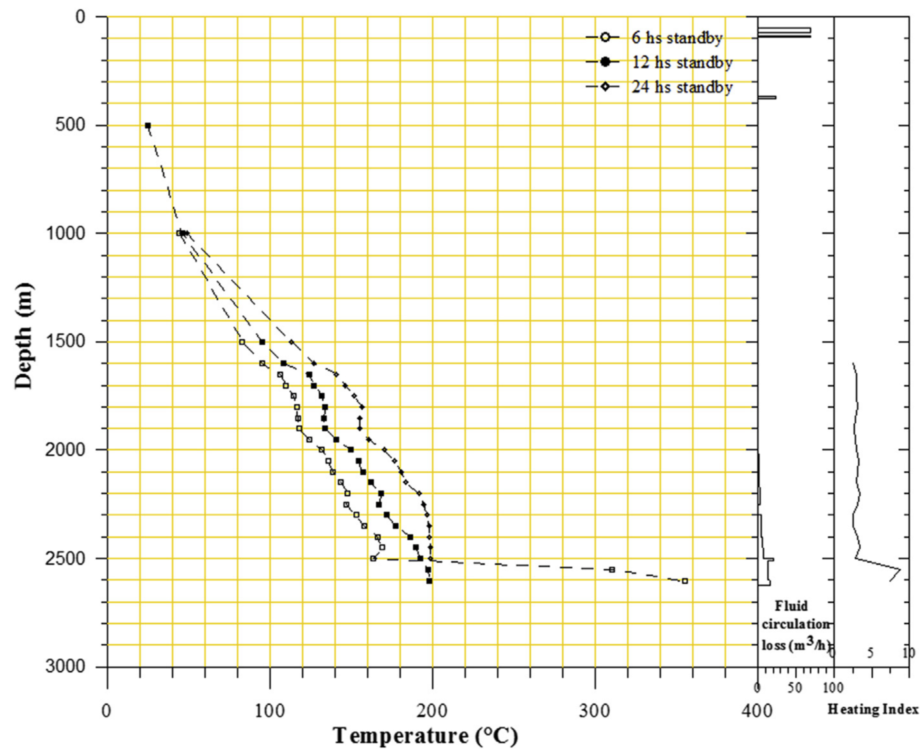

Figure 6. Profiles of temperatures logs at different standby periods, circulation losses during drilling and warm-up index of the Well 23.

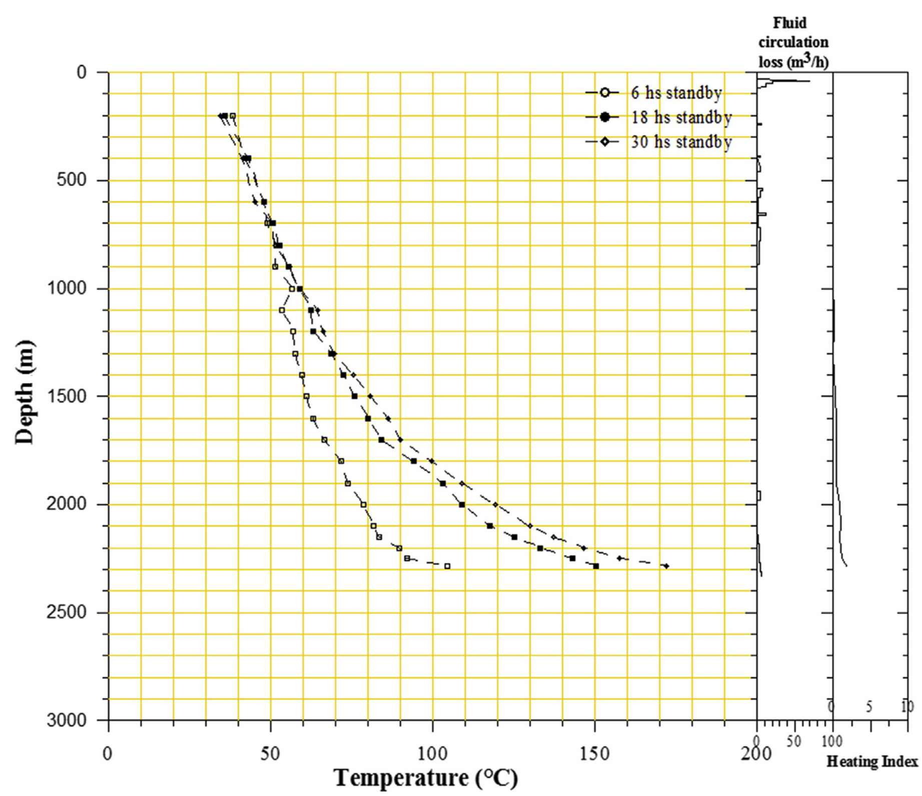

Figure 7. Profiles of temperatures logs at different standby periods, circulation losses during drilling and warm-up index of the Well 25.

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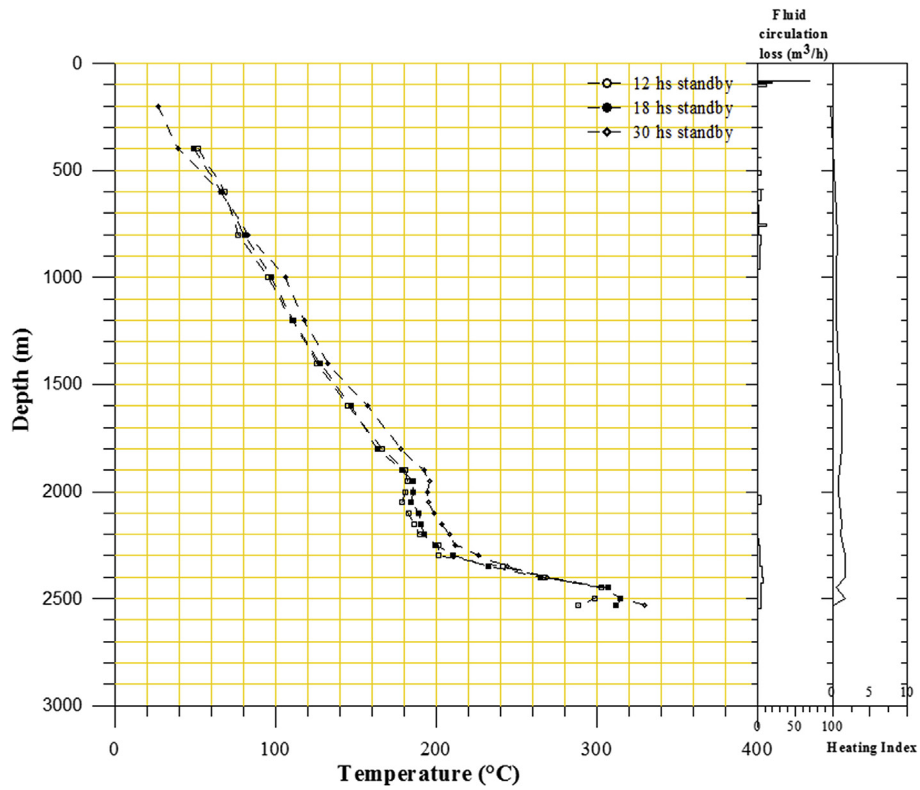

Figure 8. Profiles of temperatures logs at different standby periods, circulation losses during drilling and warm-up index of the Well 26.

same depth, each one with different stand by time, whose expression is:

$$\mathrm{HI}_j = \frac{\Delta t}{\Delta T} = \frac{t_i - t_{i-1}}{T_i - T_{i-1}} \tag{2}$$

where T is the repose time in the well; t is the temperature measured in (°C), sub index (i) is the logging number related to the repose time in hours; sub index (j) is station depth at which temperature is measured. Aragón-Aguilar et al. (2000) and Izquierdo et al. (2002) discussed applicability of HI and their correlation with production zones of Los Humeros and Cerro Prieto geothermal fields respectively.

Temperature logs, circulation losses, and completion depths were used as comparison criteria between wells in both areas and the results are shown in Tables 4 and 5. Tables 4 and 5 show characteristics of producer and closed wells respectively. Due to topographical differences in the field, for a horizontal correlation between wells, the sea level was taken as a reference, also can be seen the mean values of circulation losses and the maximum temperatures logged at their bottom.

Most of the wells in the field were completed at similar levels (approximately 400 masl), with the exception of Wells 1/1D, which were completed at a higher level. However, for similar reference levels the steady state temperatures differ between producers and closed wells, being higher in producers. In closed wells the average temperature at pseudo-steady state conditions was determined lesser to 300 °C with exception of Well 26 (360 °C). In producer wells, mean value of temperature at pseudo-steady state was found about 330 °C.

Data shown in Table 5 indicate that in closed wells, temperatures are slightly lesser than in producers. In practical terms, average temperatures of 280 or 330 °C represent existence of a hot reservoir. This is one of the reasons for assuming that temperature

Table 5
Summary of some of the main characteristics such as completion levels, fluid circulation losses, measured temperatures of closed wells in LHGF.

Well	Completion levels (masl)	Fluid circulation losses (m^3/h)	Maximum logged temperatures (°C)	Interval from $t = 200$ °C (masl)
23	300	20	295	370–690
25	540	6	270	550–575
26	470	8	360	320–700
27	340	15	280	300–700

Table 4
Summary of main characteristics (completion levels, feed intervals) of producer wells in LHGF, their measured temperatures and water flow, steam flow and enthalpies of produced fluid.

Well	Completion levels (masl)	Fluid circulation losses (m^3/h)	Maximum logged temperatures (°C)	Water production (t/h)	Steam production (t/h)	Steam fraction	H_f (kJ/kg)	Feed interval (masl)
1	1430	50	320	31	32	0.51	1400	1370–1500
6	400	7	360	3	29	0.91	2410	420–560
7	450	5	335	0.5	33	0.98	2660	500–640
12	350	4	360	2	26	0.93	2620	1350–1470
39	390	18	300	4	27	0.87	2200	505–710

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is not a parameter which marks the difference between producer wells and the closed wells.

The particular characteristics of the Wells 1/1D are the magnitude of their circulation losses during drilling and lesser depth of the production interval in comparison with the other field wells. At the bottom of the Wells 1/1D, circulation losses during drilling were determined in the rank of 50 m^3/h. Fig. 9 shows profiles of circulation losses during drilling and temperatures logged at different standby periods along the Well 1 (originally vertical). The HI in this well was determined using logs at 18 and 30 h of standby. The completion depth of closed wells (see Figs. 6–8) is higher than that of Wells 1/1D (Fig. 9).

3.3. Productive behavior of southwestern section of the field

The Wells 6, 12 and 39, located to southwestern side of the field are producers and in continuous operation during the last 20 years. By using temperatures at steady state conditions were determined isotherms for 200 and 300 °C and were correlated, with well locations along the LHGF. Fig. 10a and b shows maps of isotherms distribution of 200 and 300 °C in the field.

The field surface is located about 2800 masl and all the wells of this study zone (central and southwestern) have their completions close to 500 masl, with the exception of Well 1, which was completed at 1430 masl. It can be seen from profiles of circulation losses shown in Figs. 6–9 that at shallower depths, circulation losses are greater than that at bottom where is located the lithological unit represented by ignimbrite. A similar behavior of circulation losses was found in the majority of field wells. The values of circulation losses at bottom are lesser than 10 m^3/h, except in the Well 1.

The measured temperatures in producer wells (ca. 320 °C), together with the values of circulation losses and steady state temperatures at these same levels are shown in Table 4.

The saturation state of analyzed wells was determined using pressure-temperature profiles at the end of drilling stage in combination with thermodynamic diagrams. Examples of temperature-pressure and enthalpy-pressure diagrams are shown in Figs. 11 and 12 using data of the Well 39. Fig. 11 presents comparison of temperature and pressure data, with the saturation curve. Fig. 12 shows the enthalpy-pressure behavior of the produced mass flow for Well 39 along its productive history. Through the enthalpy-pressure diagram, it can be determined that the fluid quality varies between 0.6 and 0.95 along production stage of this well. Figs. 3 and 12 show higher fluid quality of the Well 39, with respect to the Wells 1/1D which varies in the range of 0.4.

From the production measurements at well-head conditions and by using flow simulation program (Gunn and Freeston, 1991), bottom hole flowing pressures were determined. The pressures determined for 5 and 10 years of continuous operation were used for constructing maps of isobaric distributions, along the field, which are shown in Fig. 13a and b.

To date, at the eastern part of the central zone of the field, no more wells have been drilled due to low permeability and temperature (near 300 °C temperature found only at deeper levels).

4. Discussion

The volcanic pre-caldera deposits at LHGF are represented by andesites. These andesites alternate with basalt and ignimbrite sequences where most of the circulation losses were recorded. Main features associated to a geothermal reservoir are heat source, a basement, a seal cap, permeable rock formation and recharge by water entrance, among others (Grant and Bixley, 2011). Nevertheless in the wells located at central eastern section of Los Humeros (23, 26 and 27) only were found average temperatures of 280 °C.

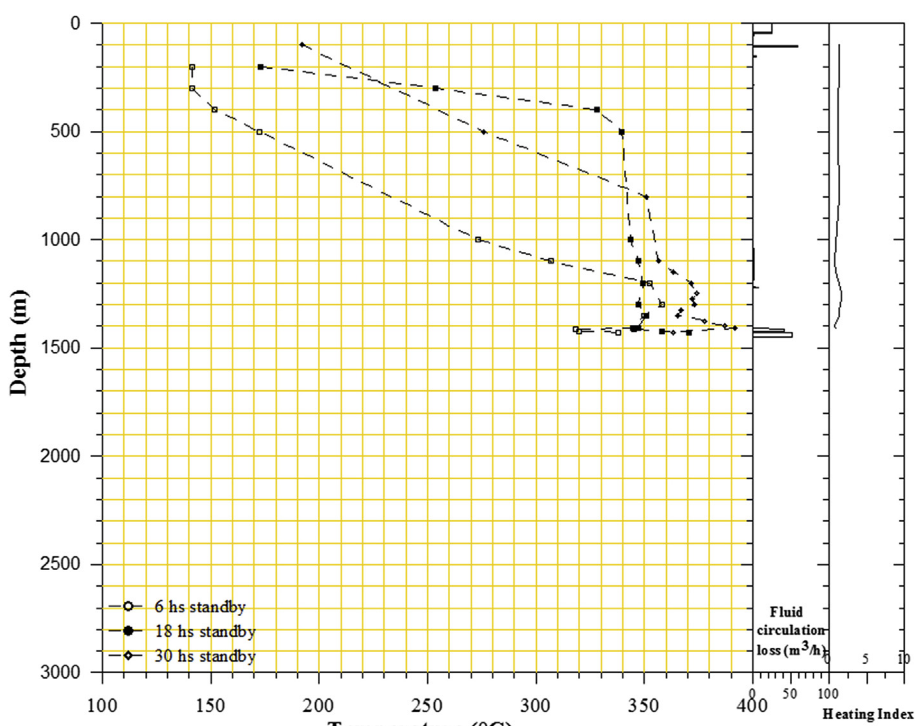

Figure 9. Profiles of temperatures logs at different standby periods, circulation losses during drilling and warm-up index of the Wells 1/1D (producers).

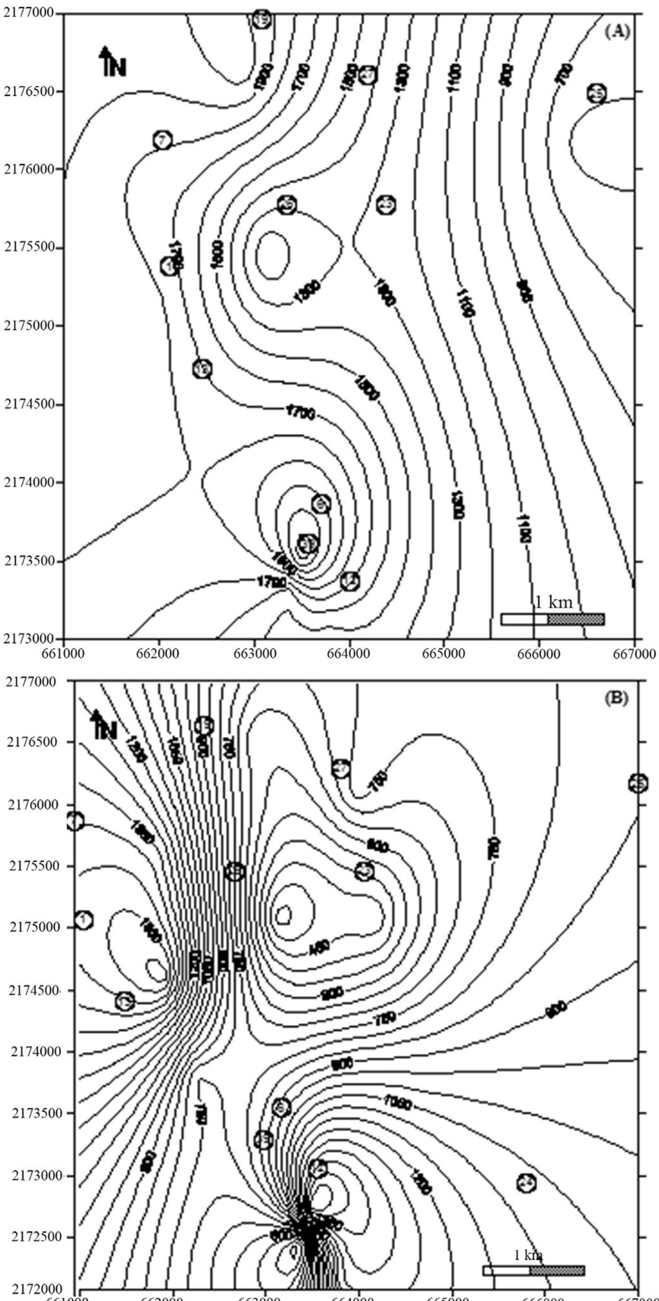

Figure 10. Distribution maps of the isotherms that were calculated to 200 °C (A), and 300 °C (B) along the LHGF.

The pre-caldera andesites have contrasting physical features among one another other. Because of the lower permeability and porosity, the intensity of hydrothermal alteration is different. However, evidence of natural permeability in the reservoir rocks is restricted to the ignimbrite that was believed to be the cap rock which shows primary and secondary permeability that is reflected in circulation losses at depth. In LHGF such layer of a porous material that could be an ignimbrite or a silicified andesite is common, and is only a mass of microcrystalline quartz with plagioclase phenocrysts and traces of chlorite and pyrite (Elders et al., 2014). The same type of material has been observed in at least four nearest wells approximately at the same depth (23, 26, 27 and 28). The authors suggest that this could be an evidence of the presence of

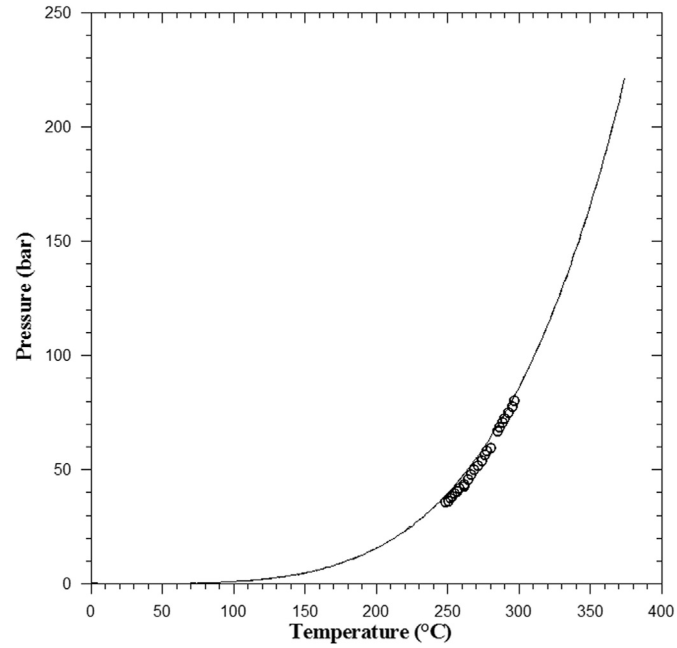

Figure 11. Graph of pressure-temperature diagram at saturation conditions showing comparison with measured data of the Well 39.

acid fluids that moved laterally through the porous rock. Locally the results of acid alteration can be seen in the reservoir rocks in the form of bleached silicified zones; which present higher permeability compared to the andesites below and above of this unit.

Evidence of low permeability is related with characteristics of lithological units shown in Table 1, together with the results of transient pressure tests, measurements of laboratory core samples and the low circulation losses during drilling. The low productivity of LHGF reservoir is due mainly to its low permeability and low recharge which in some case is null. Considering the rock formation

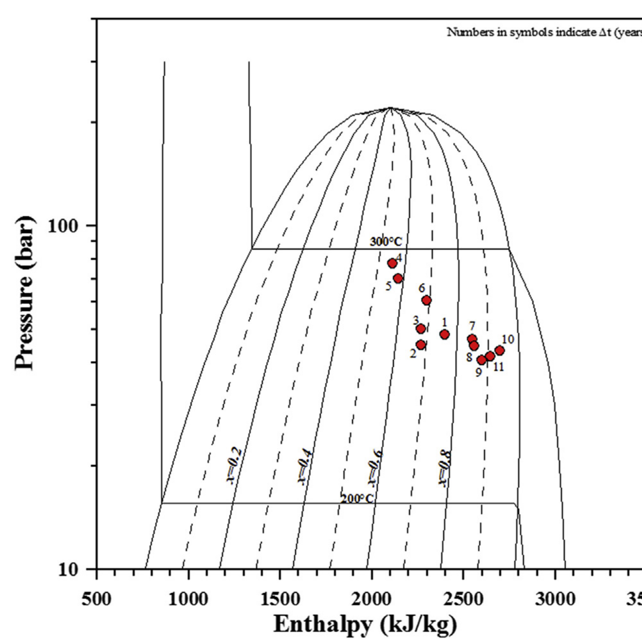

Figure 12. Graph showing enthalpy pressure of the Well 39; it can be seen that the average steam fraction of the well, increases from 0.6 toward 0.95 during its operative life.

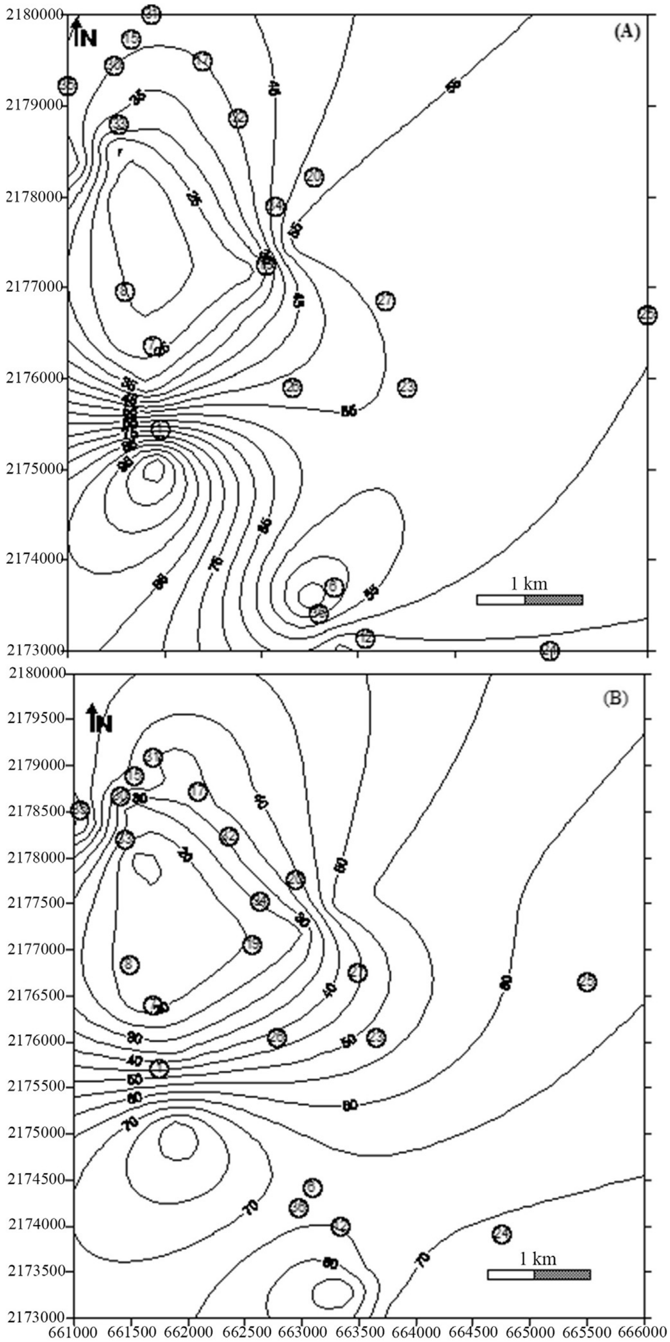

Figure 13. Distribution maps of the isobaric lines, calculated for five (A), and ten years (B) of continuous operation of LHGF.

properties, it is emphasized that in all the reservoirs, the inlet of fluid is the main parameter for maintaining their useful life. But entrance of fluid depends on the permeability of the rock formation. The low permeability of deep rocks and the absence of recharge are against appropriate conditions for the existence of geothermal production.

At the bottom of closed wells the logged temperatures is found to be lower than 300 °C (Table 5), except in Well 26 (360 °C). Temperatures show tendency to be deeper at eastern side of central zone of LHGF. The higher temperatures were found at western and southwestern side of this central zone as can be seen in Fig. 10a and b.

The zone showing more decrease in pressure during the time interval between five and ten years is at western side of the field, where the producer wells are located (Fig. 13a and b). Evolution of the fluid state of producer wells allows identifying high enthalpy with a tendency to the steam phase. In the central western zone (producer wells) temperatures higher than 320 °C were found at depth. The existence of such conditions indicates the presence of heat in the reservoir; however, due to lack of permeable conditions and fluid, heat cannot be extracted to the surface by the conventional methods.

Our methodology helps to identify zones of high temperature and the intervals of geothermal interest.

5. Conclusions

Based on the analyses and models the following conclusions are drawn:

(1) The methodology applied allows to characterize the central and southern zones of LHGF which involve neighboring wells that are productive and non-productive.
(2) Average temperatures, at bottom hole conditions, of the closed wells are 280 °C, and that of the producers are 320 °C.
(3) At depth, measurements of circulation losses during drilling indicated maximum values 10 m^3/h; which, corroborated by a review of transient pressure tests and laboratory measurements to core samples, allows us to define that the permeability is low.
(4) A good data base on the behavior in produced mass flow of Well 1 and neighbors is generated, and it is recommended that a detailed analysis of data be carried out in order to extend the knowledge of this zone.
(5) Circulation losses in the rank of 50 m^3/h were found only at shallow depths, particularly in the wells of the central and southern zone of LHGF, but are not related with geothermal reservoir.
(6) Low permeability of deep rocks restricts water entrance to the reservoir, leading to high enthalpies in production wells which under extreme conditions could result in a dry geothermal system.
(7) The analysis carried out allows to model the behavior of the well performance, which in turn will help to locate new drilling wells and to achieve successful results.
(8) It was found that productivity behavior could be related, among other factors, to low permeability of the rock formation.
(9) Results of this research allow to determine the analyzed area of the field capable for heat storage even with lack of permeability.
(10) It is recommended to apply techniques of reservoir engineering (transient pressure tests) for verifying the faults and their distance to wells.
(11) The fluid state of producer wells allows identification of high enthalpy in LHGF with a tendency to the steam phase.

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